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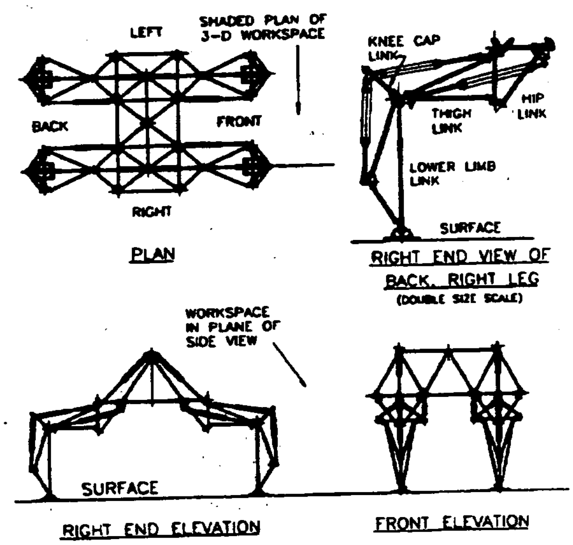
(54) Title: SPACE TRUSS INTEGRATED-CONSTRUCTION ROBOT

(57) Abstract

A space truss integrated-construction mechanical structure for a novel robot is disclosed. The space truss structure is entirely made of tetrahedral building blocks or structures that form rigid space frames and rotary dynamic links which can each be moved by a linear actuator or drive such as a pneumatic or hydraulic double acting cylinder (see Figs. 1 to 4). All fixed length connection members (5, 14, 24, 25, 31, 32, 33) or linear actuators (1, 6, 15, 19) on the space truss stucture are connected at their ends to tetrahedral vertex nodes which are made up of a combination of solid, rotary or spherical joints. This is an important feature of space frames which is exploited to achieve very high stiffness-to-weight ratios for the mechanical manipulator links. The robot has four legs (see Figs. 1 and 4), each of which act as an articulated-link manipulator that controls an end-effector or foot (34) on the tool plate of its last link relative to the moving or stationary base or body, via serially connected rotating links. The knee cap link (see Fig. 1) shares the same rotary degree-of-freedom as the lower limb link and serves to increase the range of motion of the lower limb link relative to the thigh link from an angle less than or around 90° when only one linear actuator (15 or 19) and one fixed length connection member are attached to its top node (16), to a range of motion up to or around 170° by using two attached linear actuators (15 and 19). The integrated-construction features of the invention include the ability to proportionately increase or decrease the overall size of a given shape or form of its structure without changing its nodes, the capability to add or remove tetrahedral structures to or from existing tetrahedral structures or links, and the ease of assembling and disassembling all c mponents and c nnection members of the robot without damaging parts or using cutting processes.



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SPACE TRUSS INTEGRATED-CONSTRUCTION ROBOT

This invention relates to strength and weight saving mechanical design improvements for teleoperated, automatic or robotic manipulator arms and articulated-limb mobile robots.

The majority of robotic arms and articulated serial-link manipulators used in industrial applications display some or all of the following problems:

- They are usually very heavy due to the excessive use of structural material to cope with large static and dynamic loads.
- Deflection in the links of most manipulators reduces the absolute positional accuracy of the end-effector or tool being controlled.
- The large mass moments of inertia of the links tend to slow down system response and contribute to undesirable overshoot and system instabilities in closed-loop control servo systems.
- Mechanical and electrical energy efficiency is low and near optimal performance is impossible.
- The purchasing cost of a new industrial robotic arm with its controller ranges anywhere from US$40,000 up to US$200,000 or more. Hence, implementing conventional manipulator arms would incur a substantially large investment cost to most manufacturing businesses.
- The majority of commercially available robotic manipulators are not easy to alter or expand to suit different applications. For example, standard 6 degree-of-freedom robot arms are being used in operations that can be accomplished with fewer degrees-of-freedom, hence money is wasted in purchasing more equipment than a process demands. Some applications may require larger end-effector reaches beyond those specified by standard commercially available robot models.

There have been attempts to solve some of the above mechanical problems in articulated link manipulator design. For example, hollow rectangular prisms or box-shaped links made of lightweight metal or polymer plastics are being used on some industrial manipulators and mobile robot legs. Although such designs provide large cross-sectional moments of inertia for high resistance to bending moment

deflection, the weakest points usually exist around the ends of such links. Rotary bearings are housed or embedded into the plate-like walls at the end of such links. These bearings transmit the end-effector load from link-to-link towards the base of the manipulator. Hence, if a large twisting torque acts on the last link, rotational deflections are likely to accumulate from link to link and reduce end-effector accuracy. This problem is significant when using thin-sectioned lightweight and low strength materials such as aluminium or plastic. For example, if articulated limbs are used on a wall climbing robot, the weight of the body transmits torques to the individual manipulator-like legs that have their vacuum feet stuck onto the wall's surface. This causes the legs to deflect so that the effective strength of the stressed material around the link bearings reduces and the high stress concentrations which develop are likely to cause crack growth at sharp corners or edges. Other designs aim to save weight by using thin plates with large notches and holes cut out, but this reduces the strength of such material, making structures more susceptible to buckling and deflections when heavily loaded. The aforementioned designs do not result in optimum material usage and performance. They also do not allow for flexibility in easily extending or reducing the range of motion and the number of degrees-of-freedom of the manipulator arm to suit an application.

The present invention solves all of these problems and provides near optimum strength-to-weight ratios for static and dynamic structures of robots and manipulator links due to a novel space frame construction method using tetrahedrons as the basic building block. The construction technique will be outlined in the descriptions of the 4-legged "SPACE TRUSS INTEGRATED CONSTRUCTION ROBOT" (abbreviated as STIC robot or STIC Mk 1, the Mark 1 version) and in the detailed discussion of the 3 degree-of-freedom serial-link manipulators which serve as the articulated-limb legs on the STIC robot. The leg manipulator is also useful as an independent robotic or teleoperated arm for manipulation of an end-effector or tool. In describing the technical features of the STIC robot which incorporate the manipulator legs, the following list of special terms (shown underlined) will be used:

- A connection member is a slender rod, bar, tube or hollow section that has a high length-to-width ratio, usually greater than 10, and connects two different joints at the opposite ends of the connection member. This term also applies to linear actuators such as cylinders where the connection member is of variable length, limited only by the actuator stroke length.
- A connection plate is a solid, high strength rectangular-prism-shaped flat bar or tab having a hole situated on a flat surface for inserting the end of a connection member, bearing or actuator rotary joint. These are located at nodes for making solid joints.
- A solid joint is a rigid or fixed geometrical relationship between the end of a connection member and a connection plate. Solid joints are situated on nodes at the vertices of tetrahedral structures.
- A rotary joint allows a node to rotate about a connection member's axis by means of a ball bearing or bearing bush housed in that node, or it can be a bearing at the end of a linear actuator, such as a cylinder, that allows the end of the actuator to rotate or pivot relative to a solid joint on a space frame or a solid joint on a moving link. Like solid joints, rotary joints only occur at the ends of connection members or at nodes.
- A shaft is a rotating connection member on a link that must have rotary joints situated at its opposite ends. Shafts are usually members of links.
- A spherical joint is a ball and socket connection that allows a node or end of a linear actuator to rotate about the centre of the fixed ball in a spherical manner, giving the attachment two rotational degrees-of-freedom.
- A tetrahedral structure is any portion of a space frame which can be identified as a pyramid having 6 connection members that form 4 triangular faces and 4 tetrahedral vertices of the triangular sides. The connection members and nodes of a tetrahedral structure may be shared by neighbouring tetrahedral structures.
- A tetrahedral vertex (plural form: vertices) is a general term referring to a group of joints or nodes in very close proximity to each other, occurring at the end of a connection member in a space frame. The distances between separate nodes

and joints belonging to a tetrahedral vertex are small in comparison to the length of the shortest connection member in the space frame.

- A link is a tetrahedral structure designed to rotate about one or more shafts which form part of the tetrahedral structure's connection members. It normally consists of 4 or 5 connection members joining its nodes, 1 or 2 connection members acting as shafts, and one actuator.
- A rotary degree-of-freedom of the STIC robot refers to the ability for a link to rotate about a shaft axis relative to another link or space frame. This term may also apply to the pivoting motion of the end of an actuator relative to a node via a rotary joint.
- The term space frame refers to a three-dimensional structure that concentrates forces at the nodes of vertices on the tetrahedral structures. Thus, forces are transmitted through connection members by axial compression or tension so that the joints at the nodes must handle almost all stresses due to bending moments and shear forces.
- A node is a collection of the same type or different types of joints situated at a tetrahedral structure's vertex in a space frame. A node must be compact so the joints do not undergo extreme bending moment stresses. A node may consist of a bearing housing or solid thick block to which connection plates and other forms of joints may be attached or welded. It may also take the form of strong flat or thick bent-to-shape metal or cast material with the holes of connection plates at correct positions and orientations for making solid joints. The space truss nodes of the STIC robot can be categorised into the following types according the joints at the node: (A) All solid joints; (B) Part solid, part rotary joints; (C) Part solid, part spherical joints; and (D) Part solid, part rotary, part spherical joints.
- The body refers to the rigid space frame at the centre of the STIC robot that excludes the movable links, actuators and end-effector tools. The body contains 8 tetrahedral structures arranged side by side to form the width of the robot. The term body may also apply to the stationary rigid space frame that forms the base of a manipulator used independently as a robotic, remotely controlled or automatic manipulator arm.

- A leg is equivalent to the term manipulator and consists of links connected in series with each other which branch off from rotary joints on the nodes of the base plane of the body. These legs are not considered to be part of the robot body, since they are dynamic structures and not rigid.

The essential features of the STIC robot mechanical structure are numbered as follows:

1. The robot can walk over unstructured (or non-planar) surfaces by using special customised feet fixed to the ends of the manipulator legs. The robot employs appropriate sensors, controllers, electronic and electrical interfacing, controlling computer software or manual remote controls and one actuator for each rotating link activated by a readily available power source.
2. The robot is capable of walking forwards, walking backwards, stepping sideways, rotating on the spot, steering left and steering right while moving over smooth, flat surfaces. Vacuum feet are necessary for vertical wall climbing or upside-down ceiling walking.
3. The robot may perform floor-to-wall, wall-to-ceiling and ceiling-to-higher-wall surface transitions automatically under computer control. This includes most types of 3 dimensional inter-planar and unstructured surface changes within the range of internal 90° corners (eg. floor to wall move) to external 90° corners (eg. ceiling to a higher wall move), with varying angles of approach.
4. The STIC robot can carry payloads of much greater weight than the total weight of the robot's structure. Near minimal deflection occurs in the links due mainly to the high strength and low weights of the tetrahedral structures and the rigid space frame body.
5. The linear actuators that move the tetrahedral-shaped links relative to each other solely determine the ranges of motion for each of the rotary degrees-of-freedom between pairs of links, so that no mechanical end stops are built onto the space frame connection members. Such mechanical end stops would otherwise induce forces that could not be distributed well to other nodes and would concentrate stresses on individual connection members.

6. Space frame structures may be added to or removed from existing space frames in a modular fashion. For example, the body of the STIC robot may be widened to accommodate extra legs or extra manipulator arms. Links connected in series with one another may be removed or added to existing links. This allows the flexibility of extending or reducing a manipulator's number of degrees-of-freedom and its maximum end-effector reach (distance away from the base or body), so that economical designs may be tailor made to suit an application using the minimum number of links. Expansion of a structure is achieved by replacing existing nodes with larger nodes that have more joints, attaching connection members to these and completing the new tetrahedral structure(s) with custom made nodes.
7. All STIC space frames can be easily disassembled and reassembled for maintenance and repair without damage to any parts.
8. The STIC robot and the manipulators are adaptable to small and large scale structures for given node sizes. For example, a small STIC robot having short connection members may be transformed to a large STIC robot by increasing the cylinder sizes, stroke lengths and connection member lengths in proportion to each other. Hence, the same nodes may be used for small and large space frames but within the limits set by the strength or load capacities of the joints.

The preferred and optional features of the STIC invention and its different forms are numbered as follows:

1. It is preferable that all actuator loads and external forces are to be directed at the space frame joints (or nodes) and not on any individual connection members of the tetrahedral structures so that all connection members may be loaded axially (as in a 'pin-jointed' model) and large bending moments do not arise and permanently damage components. Effective load sharing or force distribution can be arranged by proper sizing and angular placements of connection members relative to each other.
2. The links may be moved by pneumatic, gas, hydraulic, electrical or any other power sources.

3. It is preferable to use double acting cylinders which pneumatically or hydraulically move a piston rod at one end because such actuators are compact, easily replaceable and do not require gearing. Also, the ends of linear actuators such as cylinders may be attached to different rotary joints at space frame nodes so that extension or retraction of the piston rod can move one link relative to another link usually through a range of motion of no greater than 90°. Motor driven linear drives such as high reduction ball screws, worm gears and rack and pinion gear transmissions may be implemented between such rotary joints, but these usually require more space than cylinder actuators. The use of pneumatic cylinders acting as controllable 'muscles' between the links enables easy implementation of stiffness and force control techniques, whereby opposing forces are generated on both sides of a piston due to controlled pressures.
4. The long slender connecting members may be made of either plastic, solid polymer or metal in the forms of strong pipe or tube, solid round rod, solid bar of any cross section or any type of rolled hollow section (RHS). The preferred material is aluminium round rod since this is easy to cut to length, machine and thread at the ends for fastening at solid joints.
5. Joints or nodes may be made of any type of strong, solid material such as metal or plastic. To achieve lightweight structures, aluminium or plastic polymer is preferred. For metals, connection plates may be bolted on or welded to nodes or the nodes may be entirely cast or extruded. For plastics, moulding or casting techniques would produce near finished shapes.
6. In the design of the STIC robot, a solid aluminium round rod is used as a fixed length connection member where both ends of the rod are shouldered so that the stepped-down shaft diameters at the rod ends may be threaded and inserted with clearance fits through holes of connecting plates for securing with threaded nuts or fasteners. The nuts are tightly screwed to clamp the connection plates against the shoulders of the connection member on opposite ends of the rod to ensure solid joints at the two nodes being connected. A solid joint may also be achieved by welding the connection member to a node.

7. A rotary joint may take the form of a standard bearing bush or any type of ball bearing device that allows rotation about a shaft axis. Preferably, the outer round surface of the bearing should be lightly press fitted or fixed into a node or bearing housing so that the inner diameter surface of the bearing may allow only the rotation of a shaft or actuator connection pin to occur. In the case of using a standard deep groove ball bearing, the inner race should be press fitted to the stepped-down diameter section at the end of a shaft, so that the bearing is constrained from moving along the axis of the shaft by a shoulder on one side and a nut screwed on the threaded portion at the other side of the bearing. Each deep groove ball bearing can have its outer race held from moving axially in a housing or a bored hole of a node by means of circlips or coverplates with screws.
8. A spherical joint may be a commercially available "ball and socket" type joint or a universal joint. Care should be taken to ensure that adequate ranges of motion for a joint can be achieved to obtain desired ranges of motion of the dynamic links or attached actuators.
9. The sensor mountings serve to hold each position sensor stationary with respect to its respective rotating shaft to provide positive rotational displacement for each sensor. The type of sensor may be a resistive potentiometer, optical encoder or any other type of sensor that outputs an analog or digital voltage signal or mechanical response for representing the position of the link to which it is attached relative to the previous link which is closer to the body.
10. Mechanical end stops may be added to connection members to restrict the range of motion of links, but careful selection of linear actuator stroke lengths will ensure that forces are directed to nodes even when links are at the ends of their respective ranges of motion.
11. At the end of the last link (farthest away down the chain of links from the base or body) of a manipulator or leg, a type A node is situated having a connection plate (tool plate) for attaching a gripper, tool or other form of end-effector. In the STIC robot, a spherical joint is bolted on to this tool plate to act as an ankle for a spring centred foot.

To assist with understanding the invention, reference will now be made to the accompanying drawings which show one example of the invention, namely, the STIC Mk 1 or Mark 1 version.

IN THE DRAWINGS:

FIG. 1 shows the SPACE TRUSS INTEGRATED CONSTRUCTION ROBOT (Mark 1) in the "standing upright" position, displaying the orthographic projection views: PLAN (top view), RIGHT END ELEVATION and FRONT ELEVATION. It shows the robot's entire assembly which includes the space truss body, double acting cylinder actuators and the four manipulator legs. Each leg has three rotary degrees-of-freedom and four degrees of mobility due to the presence of four links, two of which share the same rotary degree-of-freedom. Each leg is shown with the HIP LINK in a horizontal orientation, the THIGH LINK in a centred position relative to the HIP LINK, the KNEE CAP LINK inclined at 45° to the horizontal plane and the LOWER LIMB LINK having a vertical orientation. Many different configurations of the legs exist within actuator constraints but are not shown. The PARTS LIST on Page 15 of this document describes all the major components of the STIC robot and shows respective quantities. It must be noted that each of the referenced major components shown in the PARTS LIST may be composed of many small parts that will not be referenced but may be described in brief.

FIG. 2 shows a close-up or enlarged drawing of the RIGHT END ELEVATION of the STIC robot showing the side view of the manipulator legs in one configuration, as from FIG. 1. Due to symmetry, this view is identical to a LEFT END ELEVATION in third angle orthographic projection based on the LEFT side indicated on the PLAN view of FIG. 1.

FIG. 3 shows a close-up or enlarged drawing of the FRONT ELEVATION of the STIC robot showing the front view of the robot legs in one configuration, as from FIG. 1. Due to symmetry, this view is identical to a BACK ELEVATION in third angle orthographic projection based on the BACK side indicated on the PLAN view of FIG. 1.

FIG. 4 shows a close-up or enlarged drawing of the PLAN of the STIC robot, as from FIG. 1, with the robot legs in one configuration. Hidden from view are the diagonal connection members or braces on the base plane of the robot body because they are overlapped by the sloping connection members 32. Using the PLAN view in FIG. 4, the following list describes the connections on the base plane of the body which can not be seen from the third angle orthographic projection views of FIG. 1. For the STIC robot body:

- RIGHT SIDE: Connection member between BACK RIGHT node 27 and FRONT RIGHT node 28
- MIDDLE: Connection member between BACK RIGHT node 28 and FRONT LEFT node 28
- LEFT SIDE: Connection member between BACK LEFT node 28 and FRONT LEFT node 27

These figures and the PARTS LIST will be referenced in the following technical description of the STIC robot.

DESCRIPTION OF THE HIP LINK

The hip link includes the components that are referenced by numbers 2, 3, 4, 5, 7 and 8 on Figures 2 to 4. It has one "pitch-like" rotary degree-of-freedom with respect to the horizontal body and can be moved or locked into a fixed position by the hip link actuator 1. Nodes 2 and 3 contain bearings and solid joints for attaching the connection members 5. The connection member between 2 and 3 acts as a hip shaft that is rigidly connected to the robot body with solid joints at nodes 26 and 28 or nodes 27 and 28. At the end of the hip shaft that is attached to an outer corner node 26 or 27, is a protrusion or narrower diameter shaft beyond the solid connection (at 26 or 27) where the position sensor's rotary shaft or transducer 4 may be fixed. The position sensor's rotary shaft 4 may be coupled to the end of the hip shaft as described using non-slip adhesive tape or a solid shaft coupling device. This position sensor 4 for the hip link is solidly fixed to a mounting bracket that is also fixed to the outer hip link node 2, as seen in FIG. 4. As the hip link rotates relative to the body about the axis of the hip shaft, so does the body of the position

sensor 4. This causes a positive displacement of the position sensor's rotary shaft 4 which is fixed to the hip shaft to produce a varying output signal, because the hip shaft does not rotate relative to the robot body but stays fixed between nodes 26 and 28 or nodes 27 and 28 on the body. At the other end of the hip link farthest from the body are nodes 7 and 8 which hold the thigh shaft (or steering shaft) between them and provide solid joints for connection members 5. On node 7 is a rotary joint for attaching the end of hip link actuator 1 via a clevis yoke at the end of the piston rod.

DESCRIPTION OF THE THIGH LINK

The thigh link includes the components that are referenced by numbers 9, 10, 11, 12, 13 and 14 on Figures 2 to 4. It has one "yaw-like" rotary degree-of-freedom with respect to the hip link and can be moved or locked into a fixed position by the thigh link actuator 6 (also known as the steering cylinder). Node 9 has a rotary joint for connecting the piston rod end of the knee cap link actuator 15 and two solid joints for two thigh link connection members 14. Node 10 is a Type A node for attaching two connection members 14. Nodes 9 and 10 are welded to the thigh shaft or form solid joints with it, at its opposite ends, as shown in FIG. 2. At the top of the top end of the thigh shaft, there is a protrusion or narrower diameter shaft beyond the bearing housed in node 7 where the position sensor's rotary shaft or transducer 11 may be fixed. The position sensor 11 is solidly fixed to a mounting bracket that is also fixed to a solid joint of the upper connection node 7 on the hip link, such that the position sensor's rotary shaft 11 may be coupled to the top end of the thigh shaft as described using non-slip adhesive tape or a solid shaft coupling device. As the thigh link rotates relative to the hip link about the axis of the thigh shaft, so does the position sensor's rotary shaft 11 that is fixed to the moving thigh shaft, so that a varying output signal is produced. At the other end of the thigh link are nodes 12 and 13 which hold a rotating knee shaft between them and provide solid joints for connection members 14. Node 13 is a Type D node having a spherical joint for connecting the piston rod end of the thigh link actuator 6. In operations where the STIC robot is required to steer right or left, the thigh link on each leg may rotate independently of the rotation of the hip link.

DESCRIPTION OF THE KNEE CAP LINK

The knee cap link includes the components that are referenced by numbers 16, 17 and 18 on Figures 2 to 4. It has one "pitch-like" rotary degree-of-freedom with respect to the thigh link and can be moved or locked into a fixed position by the knee cap link actuator 15. This link is a triangular planar structure bounded by the knee shaft 24 and two connection members 18 as seen on FIG. 3 and FIG. 4, but it can be viewed as being part of a tetrahedral structure which shares two fixed length, non-rotating connection members 14 of the thigh link and also possesses a dynamic connection member or actuator 15 that changes its length. Node 16 has two solid joints for attaching two connection members 18 and has two rotary joints for attaching the clevis yoke piston rod end of the knee cap link actuator 15 and the rear end of the lower limb link actuator 19. Nodes 17 at the base of the knee cap link triangle contain housed bearings which allow the knee shaft 24 to rotate relative to the knee cap link. Each knee cap base connection node 17 has a single solid joint for joining a connection member 18, as seen on Figures 3 and 4. A position sensor's body may be solidly mounted on node 12 of the thigh link to measure the angular position of the knee cap link relative to the thigh link by having the position sensor's rotating shaft coupled to the end of the knee shaft 24. The optional feature of using a position sensor on the knee cap link as well as the avoidance of link collisions are the main reasons for having both base nodes 17 as the outermost nodes on the ends of the knee shaft 24.

DESCRIPTION OF THE LOWER LIMB LINK

The lower limb link includes the components that are referenced by numbers 20, 21, 22, 23, 24 and 25 on Figures 2 to 4. It has one "pitch-like" rotary degree-of-freedom with respect to the thigh link and the knee cap link and can be moved or locked into a fixed position by the lower limb link actuator 19. Knee shaft connection nodes 20 are solid blocks that are pre-bored, push fitted and welded onto the knee shaft 24 to form solid joints at opposite ends of the shaft. Two short, cylindrical sleeve spacers are used on each knee shaft 24 to separate the bearings housed in nodes 17 and 12, and on the other end, nodes 17 and 13. Attached to the knee

shaft connector nodes 20 are connection plates for joining lower limb connection members 25. The lower limb apex connection node 21 has three solid joints for connection members 25 and one rotary joint for attaching the clevis yoke piston rod end of the lower limb link actuator 19. The end-effector node 22 has three solid joints for the connection members 25 and a connection hole for attaching or bolting on tools, a gripper or a mechanical foot 34. The bottom edge of the connection plates of the end-effector node 22 may be used for accurate angular alignment of attached tools and it also serves to prevent twisting of the attachment in the direction that would tend to loosen the bolted joint. At the end of the knee shaft 24 that is near node 13, is a protrusion or narrower diameter shaft beyond the bearing in node 17 where the position sensor's rotary shaft or transducer 23 may be fixed. The position sensor's rotary shaft 23 may be coupled to the end of the knee shaft 24 as described using non-slip adhesive tape or a solid shaft coupling device. The body of the position sensor 23 is solidly fixed to a mounting bracket that is also fixed to the inner connection node 13 of the thigh link, as seen in Figures 3 and 4. As the lower limb link rotates relative to the thigh link about the axis of the knee shaft 24, so does the position sensor's shaft 23 that is coupled to the end of the moving knee shaft, hence producing a varying output signal. Note that the use of the lower limb link actuator 19 can significantly extend the range of motion of the lower limb link to angles up to and around 170°. The size of the range of motion depends on the desired levels of torque required from the actuators and their stroke lengths. If only a small range of motion of less than 90° is required for the lower limb, the lower limb link actuator 19 may be replaced by a connection member joining nodes 16 and 21 so that movement of the lower limb link will be governed solely by the knee cap link actuator 15. Alternatively, the knee cap link actuator 15 may be replaced by a fixed length connection member joining nodes 9 and 16. The choice of the length and placement of a connection member for substitution of an actuator depends on the desired range of motion and achievable reach positions for the end-effector node 22.

DESCRIPTION OF THE SPACE TRUSS BODY

The space truss body of the STIC robot includes the components that are referenced by the numbers 26, 27, 28, 29, 30, 31, 32 and 33 on Figures 2 to 4. The space truss body is a rigid space frame with no moving parts because almost every joint on the body is of Type A. However, rotary joints do exist at the top outer connection nodes 29 to allow pivoting at the ends of the hip link actuators 1. The 3-hole outer corner nodes 26 and the 4-hole outer corner nodes 27 form the corners of the rectangular base plane of the robot body. Four 6-hole inner body bottom plane nodes 28 also lie in the base plane of the body. In one form of the STIC robot, all the nodes on the base plane of the body are made of one-piece bent aluminium plate with connection plate holes at their proper orientations and positions. Edges of stiffening plates or webs are welded to the adjoining edges of bent connection plates or tabs of such Type A nodes to eliminate the possibility of the connection plates forming mechanical hinges (a cause for deflection when loaded) with respect to one another. It is preferable to have all Type A nodes formed in a casting or moulding process to avoid the detrimental effects of residual weld stresses and metal working inaccuracies which may prestress connection members during the assembly process.

PARTS LIST

OF THE MAJOR COMPONENTS OF THE STIC Mk 1 ROBOT

PART No.	DESCRIPTION OF COMPONENT	QUANTITY
1	Double Acting Cylinder Actuator for Hip Link	4
2	Outer Connection Node (Type B)	4
3	Inner Connection Node (Type D)	4
4	Position Sensor mounted to end of Hip Shaft	4
5	Aluminium Round Connection Members of Hip Links	20 rods
6	Double Acting Cylinder Actuator for Thigh Link	4
7	Upper Connection Node (Type B)	4
8	Lower Connection Node (Type B)	4
9	Upper Rod and Cylinder Connection Joints (part of 7)	4
10	Lower Rod Connection Joints (part of 8)	4
11	Position Sensor mounted to end of Thigh Shaft	4
12	Outer Connection Node (Type B)	4
13	Inner Connection Node (Type D)	4
14	Aluminium Round Connection Members of Thigh Links	20 rods
15	Double Acting Cylinder Actuator for Knee Cap Link	4
16	Knee Cap Top Connection Node (Type B)	4
17	Knee Cap Base Connection Nodes (Type B)	8
18	Aluminium Connection Members of Knee Cap Links	8 rods
19	Double Acting Cylinder Actuator for Lower Limb Link	4
20	Knee Shaft Connection Nodes (Type A)	8
21	Lower Limb Apex Connection Node (Type B)	4
22	End-effector (tool plate) Connection Node (Type A)	4
23	Position Sensor mounted to end of Knee Shaft	4
24	Knee Shaft Connection Member (with spacers)	4
25	Aluminium Connection Members for Lower Limb Link	20 rods
26	3-hole Outer Corner Node (Type A)	2
27	4-hole Outer Corner Node (Type D)	
28	6-hole Inner Body Bottom Plane Node (Type A)	4
29	Top Outer Apex Connection Node (Type B)	2
30	Top Middle Apex Connection Node (Type A)	1
31	Body Bottom Plane Aluminium Connection Members	9 rods
32	Sloping Aluminium Connection Members of Body	13 rods
33	Top Rod of Body	1
34	Spring-centred Vacuum Foot	4

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A space truss integrated-construction mechanical structure which is composed entirely of tetrahedral structures with dynamic or static connection members joined to the nodes at tetrahedral vertices on the robot's space frame, the nodes, links and actuators of which provide the rotary degrees-of-freedom and ranges of motion for the robot body and its legs to stand in an upright stationary configuration, move forwards and backwards above a solid surface, steer left and steer right while moving relative to a surface, rotate clockwise or anticlockwise at one location, perform intersurface transitions such as a move from a ceiling to a higher vertical wall with appropriate vacuum feet. and perform surface transitions with various angles of approach.
2. A space truss integrated-construction mechanical structure of claim 1 wherein three-degree-of-freedom manipulators based on the body are attached and are each constructed of serially connected rotating links, each link being moved by a single linear actuator drive and joined in a chain-like fashion whereupon the last link, or link farthest from the body, holds a tool-plate for attaching tools, grippers or end-effectors to enable each individual manipulator to perform useful work or a manipulation task.
3. A space truss integrated-construction mechanical structure or robot of claim 2 wherein the knee cap link of a manipulator shares the same rotary degree-of-freedom as the lower limb link and serves to increase the range of motion of the lower limb link relative to the thigh link from an angle less than or around 90° when only one linear actuator and one fixed length connection member are attached to its top node, to a range of motion up to or around 170° by using two linear actuators attached to its top node.
4. A space truss integrated-construction mechanical structure of claim 1 wherein the nodes of the base plane of the body are made of one-piece bent plate metal or solid material with connection plates and holes at proper positions and orientations for bolting on or attaching connection members which have

shouldered and threaded ends for mating with threaded nuts, the connection plates of which are reinforced with stiffening plates joining their edges.

5. A space truss integrated-construction mechanical structure of any one of claims 1 to 4 which facilitates a large variation of its overall structure sizes while retaining the same shape or form of the structure and its nodes, a 'flexibility' feature which can be achieved by scaling the lengths or sizes of connection members and actuators in proportion to each other and replacing former connection members and actuators without altering the angles of connection plates on the nodes or without even changing the sizes of the nodes.
6. A space truss integrated-construction mechanical structure or robot substantially as herein described with reference to the accompanying drawings.

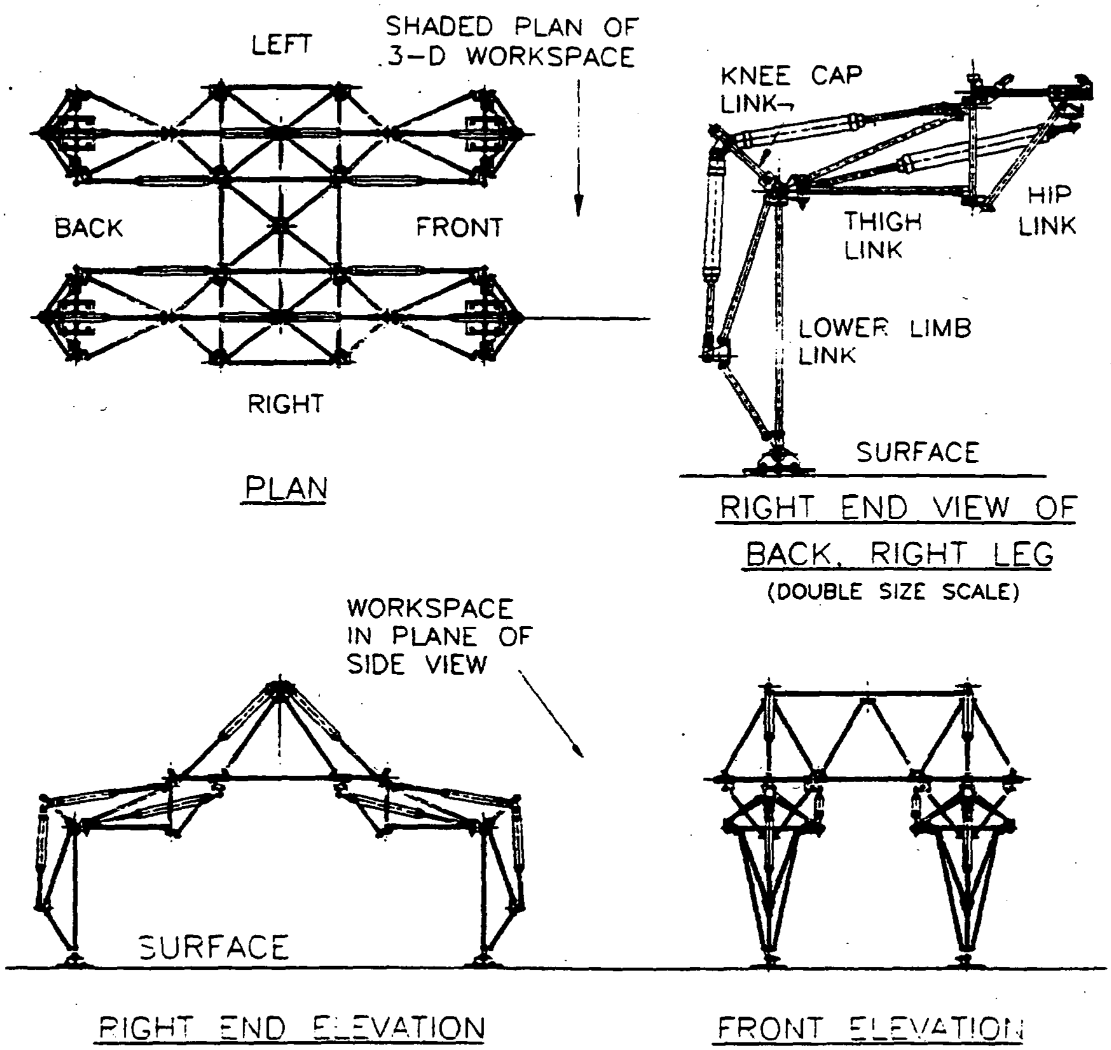
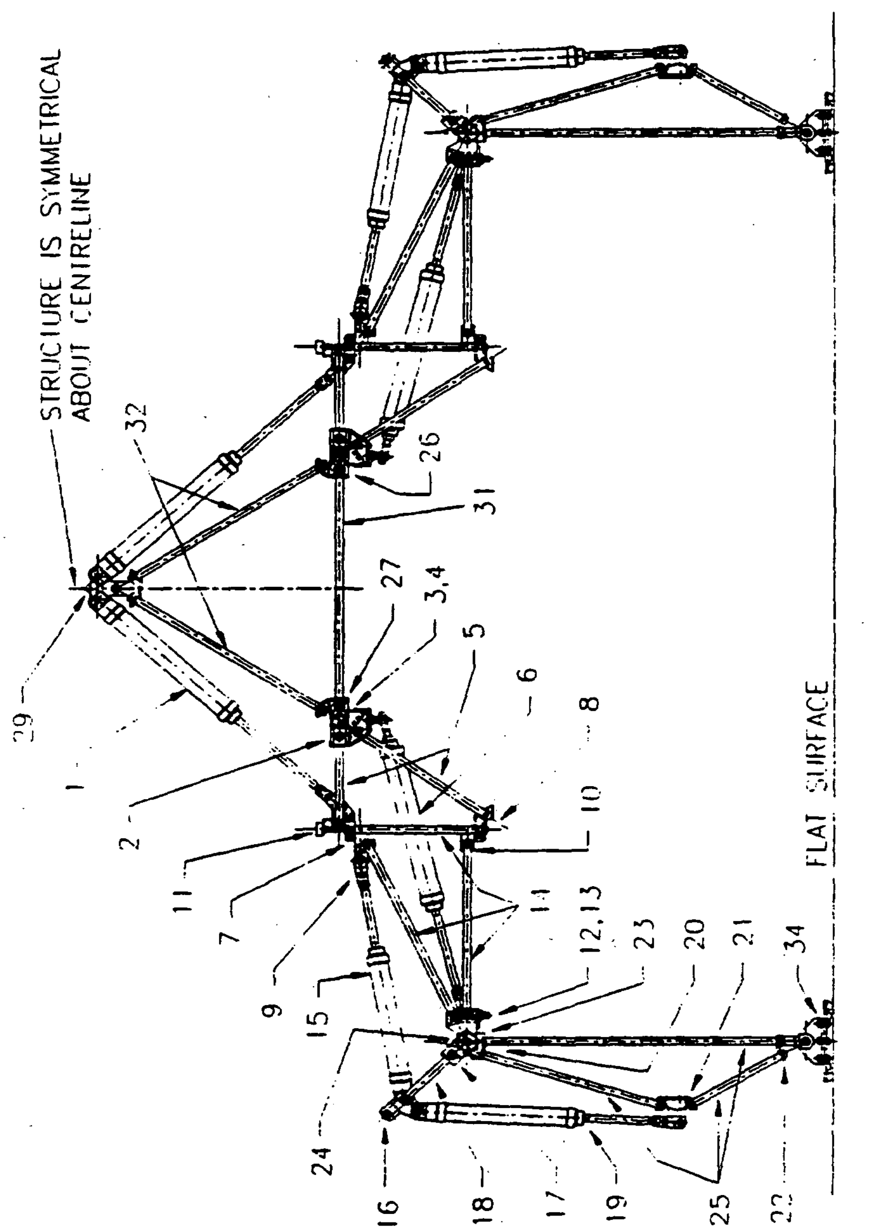
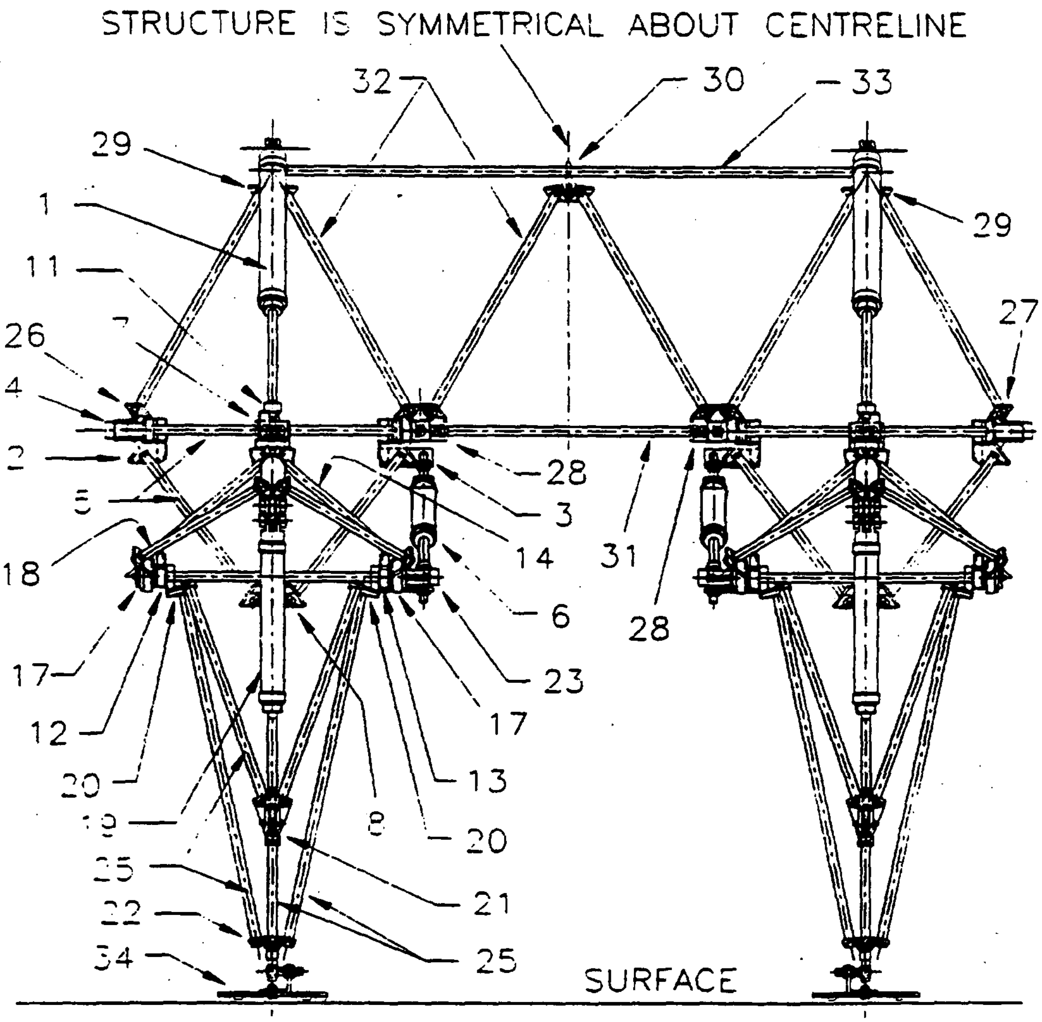

LEFT
SHADED PLAN OF 3-D WORKSPACE
BACK
FRONT
RIGHT
PLAN
KNEE CAP LINK
HIP LINK
THIGH LINK
LOWER LIMB LINK
SURFACE
RIGHT END VIEW OF BACK, RIGHT LEG
(DOUBLE SIZE SCALE)
WORKSPACE IN PLANE OF SIDE VIEW
SURFACE
RIGHT END ELEVATION
FRONT ELEVATION

Figure 1



RIGHT (OR LEFT) END ELEVATION AS FROM FIG. 1

Figure 2



FRONT (OR BACK) ELEVATION
AS FROM FIG. 1

Figure 3

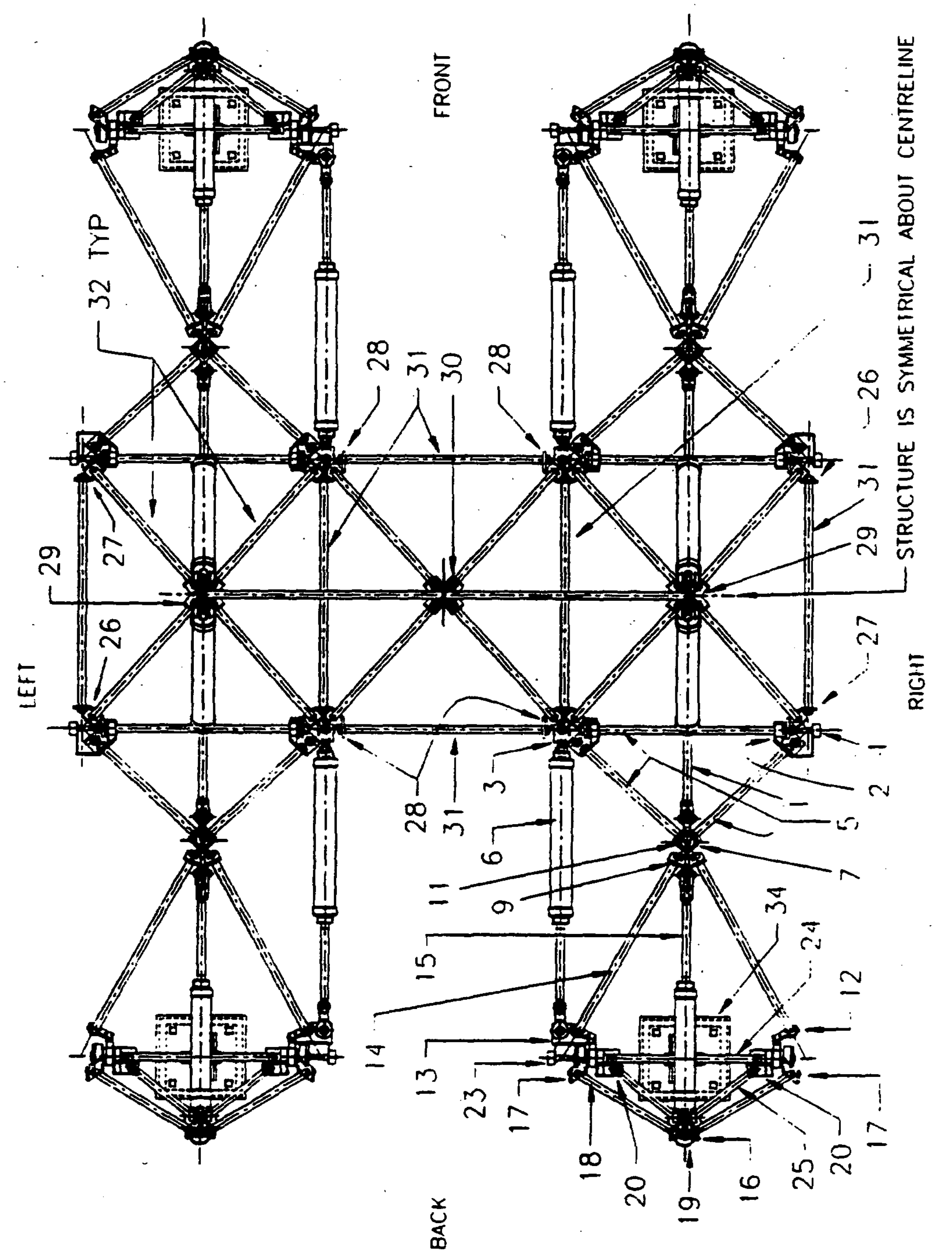


Figure 4

PLAN AS FROM FIG. 1

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 96/00026

A. CLASSIFICATION OF SUBJECT MATTER

Int Cl[6]: B25J 11/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC : B25J 11/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU : IPC AS ABOVE.

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DERWENT ABSTRACT ACCESSION NO. 020983/03, class P62, SU, 1472252, A (AZERB POLY) 20 AUGUST 1987. ENTIRE DOCUMENT	1
A	DERWENT ABSTRACT ACCESSION NO. 276542/38, class P62, SU, 1465303, A (BYRYKIN) 15 MARCH 1989. ENTIRE DOCUMENT	1

[X] Further documents are listed in the continuation of Box C

[X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
30 May 1996	11 TH JUNE 1996

Name and mailing address of the ISA/AU	Authorized officer
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INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 96/00026

C (Continuati n)	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DERWENT ABSTRACT ACCESSION NO. 170264/22, class P62, SU, 1523337, A (NOVOS POLY) 23 NOVEMBER 1989 SEE ENTIRE DOCUMENT	1
A	DERWENT ABSTRACT ACCESSION NO. 310711/50, class P62, SU, 1085804, A (HEAT POWER INSTR) 15 April 1984 SEE ENTIRE DOCUMENT	1
A	DERWENT ABSTRACT ACCESSION NO. 270228/38, class P62, SU, 1289675, A (TSELINOGRAD ENG CON) 15 February 1987 SEE ENTIRE DOCUMENT	1
A	US 5028180 A (SHELDON) 2 July 1991 SEE ENTIRE DOCUMENT	1

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 96/00026

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	5028180	AU	64300/90	BR	9007632	CA	2065260
		EP	489857	HU	61498	WO	9103145

END OF ANNEX